Evaluating Regional Model Transport Uncertainty Using Realistic LES Simulations

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1. INTRODUCTION

The Weather Research and Forecasting (WRF) model is a freely-available mesoscale atmospheric model incorporating multiple physical processes and applicable to scales ranging from thousands of kilometers (synoptic and mesoscale weather) to tens of meters (e.g., large eddy simulation (LES)). Additionally, WRF now has the capability of serving as an Eulerian transport model through its supplemental chemical and tracer code (WRF-Chem; Grell et al. 2005), and has been used in a near-real-time CO_2 emissions monitoring system to simulate atmospheric transport at high resolution (Lauvaux et al. 2013).

While mesoscale atmospheric models do not explicitly represent turbulent eddies, the ensemble-averaged turbulent kinetic energy (TKE) and turbulent fluxes are predicted through a parameterization of the atmospheric boundary layer (ABL), which are in turn used to predict the vertical turbulent transport of CO_2 in the Eulerian transport application. However, turbulent transport based on the TKE may not reflect the actual turbulent transport of a tracer over spatial scales on the order of the largest turbulent eddies (up to a few km in the well-mixed ABL), potentially leading to systematic errors in the predicted concentration of CO_2.

In this study, we will use an LES version of WRF-Chem as a tool to assess the potential uncertainty of CO_2 concentrations as simulated by mesoscale models. In LES, the largest eddies which dominate the transport are explicitly simulated. Here, we predict CO_2 concentrations from a point-source release of a case from Sep 2013 from the Indianapolis Flux Experiment (INFLUX) using a mesoscale ensemble-averaged configuration, and compare to a corresponding WRF-Chem-LES prediction.

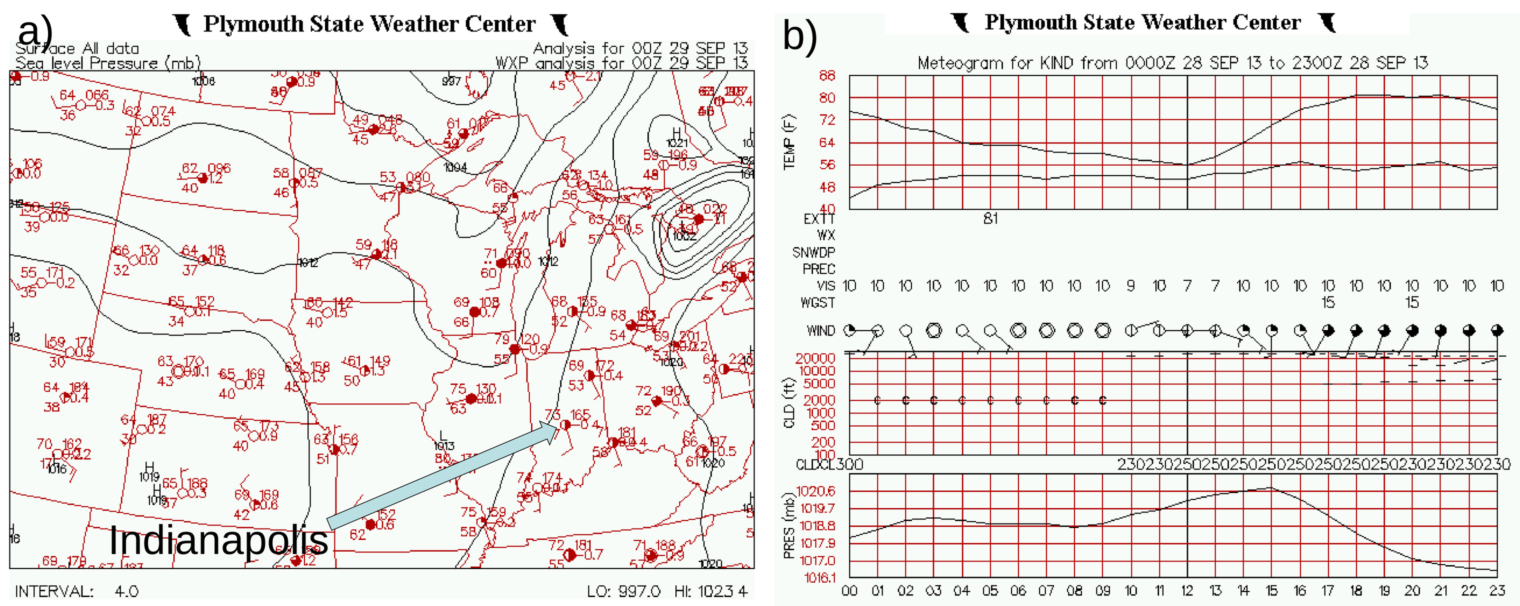

Figure 1: a) Surface meteorological map for 00 UTC 29 Sep 2013; b) surface meteogram for Indianapolis International Airport (KIND) from 0000 UTC (1800 LST) 29 Sep 2013 – 2300 UTC (1700 LST) 29 Sep 2013. Both plots courtesy Plymouth State Weather Center.

2. CASE DESCRIPTION

The case selected for study was 28 Sep 2013. On this day, the INFLUX region was in general weak southerly low-level flow in advance of a system in the Great Plains (Figure 1a). The day was precipitation-free in the area, with no clouds within 1 km of the surface (Figure 1b). The afternoon winds reported at the KIND station had an easterly component until approximately 1700 UTC, at which point the winds acquired a westerly component.

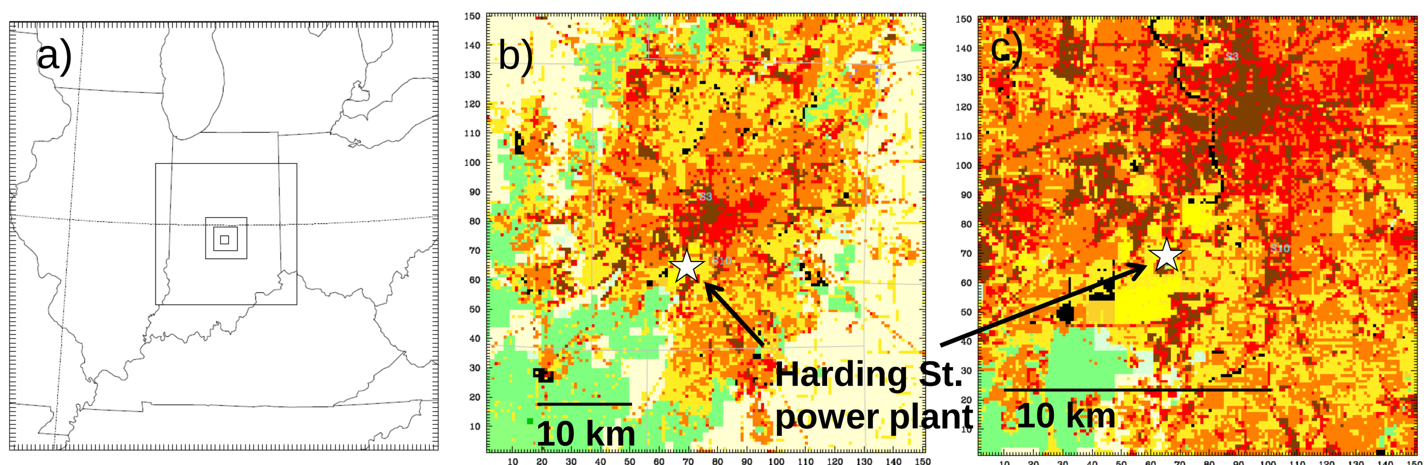

Figure 2: a) WRF model grid configuration; b) Land use characterization on 333-m mesoscale domain; c) Land use characterization on 111-m LES domain.

3. MODEL SETUP

For the WRF-Chem model configuration, we use a set of five one-way nested domains, with 9-km, 3-km, 1-km, 333-m, and 111-m horizontal grid spacing, as shown in Figure 2a. The simulation period was 1200 UTC 28 Sep 2013 – 00 UTC 29 Sep 2013. In addition to the standard meteorological fields, each domain predicts the concentration of CO_2 from different sectors (airport, commercial, industrial, mobility, non-road, residential, utility, and rail) by representing each as separate tracers within the WRF-Chem framework. The emission functions for each sector were derived from the Hestia (Gurney et al. 2012) product. Separate tracers were also introduced to represent CO_2 emissions from just the Harding Street power plant (indicated by a star in Figure 2b-c). All emissions were initially assumed to occur at the surface, but later sensitivity tests had Harding plant emissions at the stack height(s). A fine-scale remapping of the surface land use categories was used in the urban area to take into account the non-uniformity of vegetation properties for the default model urban category.

All domains except Grid 5 use a typical mesoscale model parameterization of vertical turbulent diffusion within the ABL. The finest domain, however, is run as an LES – so the vertical velocities of the largest turbulent eddies in the ABL are directly predicted by the model, and there is no need for a separate vertical turbulent diffusion parameterization.

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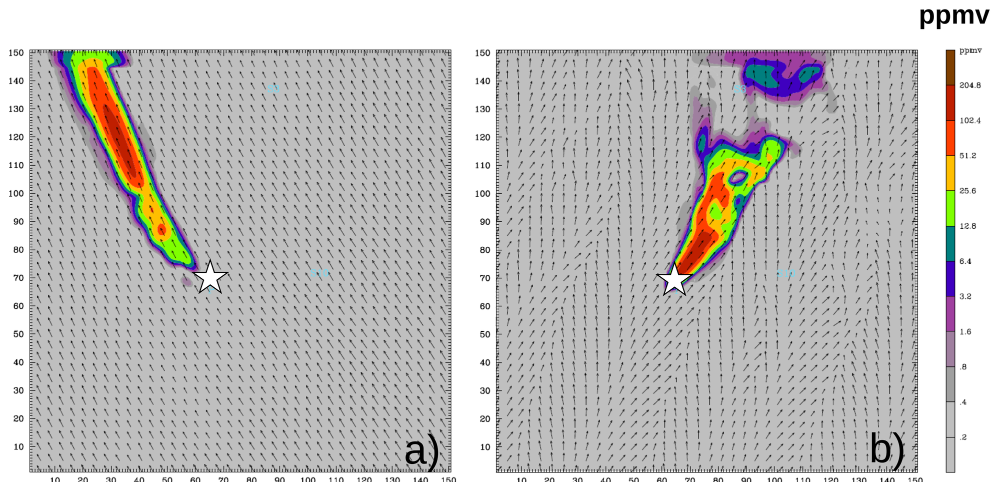


Figure 3 (left): a) Harding Plant plume concentration at 90 m AGL and 1300 UTC (0700 LST) in 111-m LES domain; b) same, but at 1800 UTC (1200 LST)

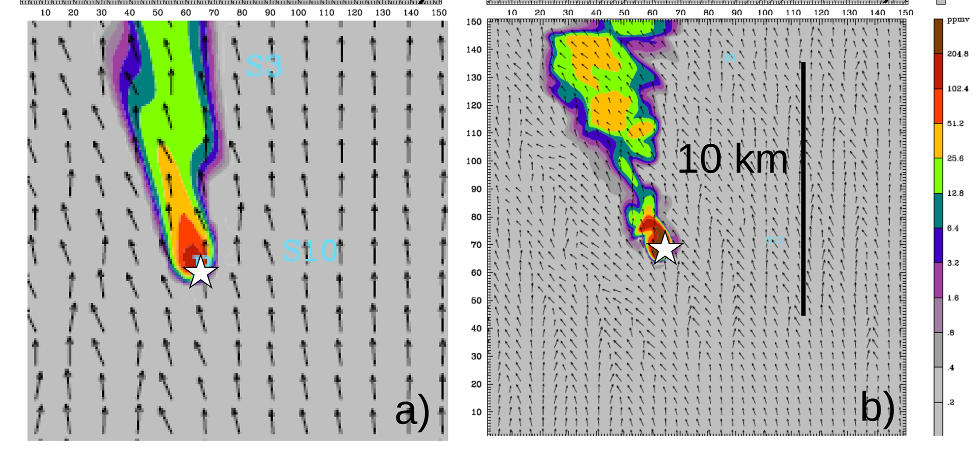


Figure 4 (left): a) Harding Plant plume concentration at 40 m AGL and 1600 UTC (1000 LST) in 333-m mesoscale domain; b) same, but for 111-m LES domain

4. MODEL PLUME HORIZONTAL STRUCTURE

In general, the model meteorology was found to match the observations fairly well. In the first part of the simulation, the plume trajectory is to the northwest (Figure 3a). Since in the early morning hours there is little solar heating of the surface, turbulent eddies in the ABL are weak, there is little vertical turbulent diffusion, and the plume is relatively concentrated. Later in the period, when the flow becomes westerly, the plume trajectory reorients to the northeast (Figure 3b). Furthermore, as solar heating increases, so does turbulent diffusion, and the plume concentrations show decreased average concentrations and more structure.

Figure 4 is an example comparing the plume structure at 40 m above ground level (AGL) between the 333-m mesoscale domain (left) and the 111-m LES domain (right). Figure 4a has been zoomed on the Harding Power Plant region such that both Figure 4a and Figure 4b cover the same spatial area. It can be seen that while the plume trajectories and average concentrations are similar, the LES plume shows much more irregularity, with zones of both increased and decreased (or near-zero) concentrations.

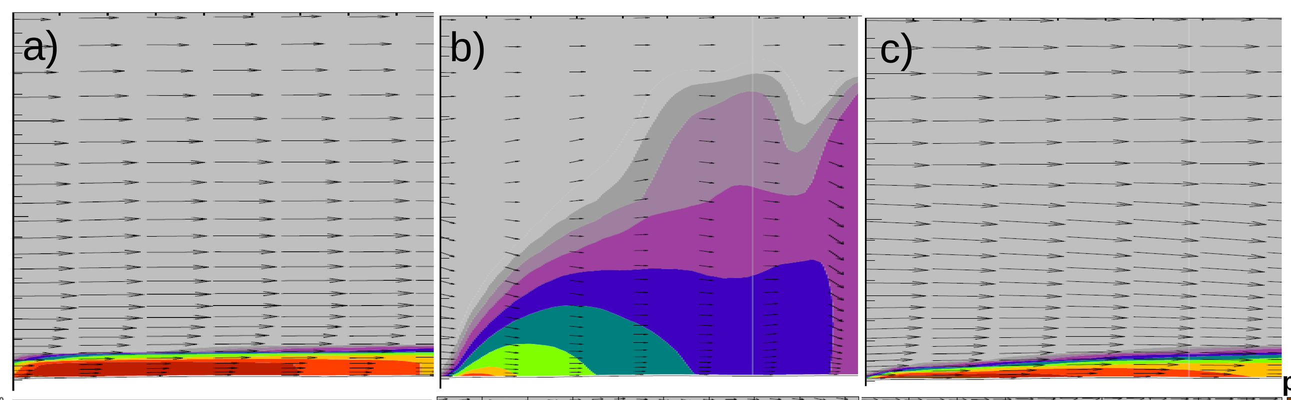


Figure 5 (left): a) Average Harding plant cross-plume concentrations in 333-m mesoscale domain at 1300 UTC (0700 LST); b) same, but for 1800 UTC (1200 LST); c) same, but for 0000 UTC (1800 LST).

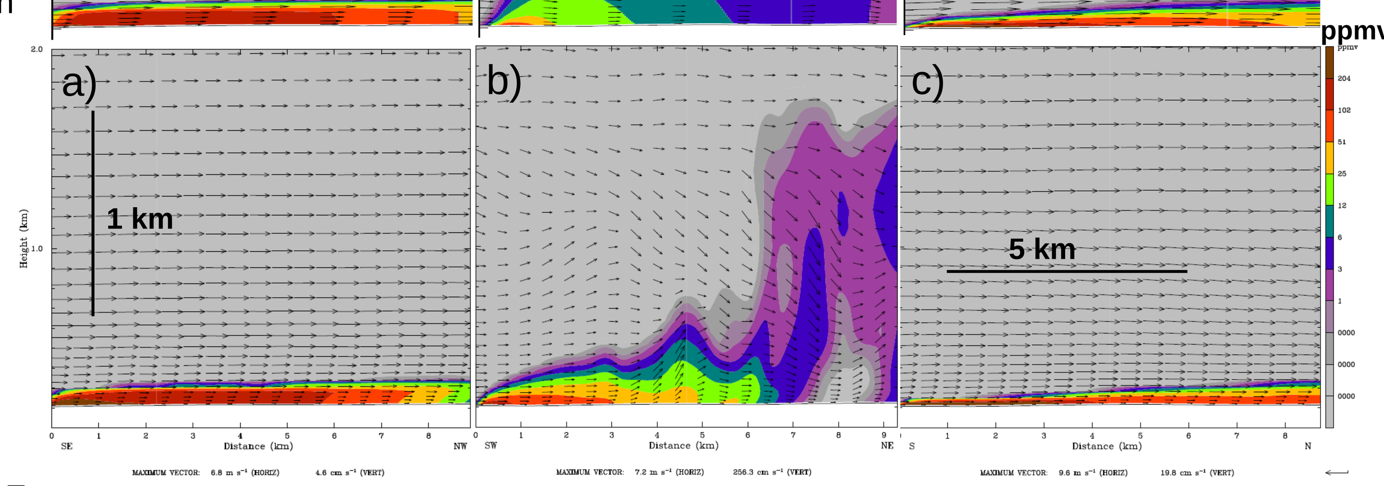


Figure 6 (left): a) Average Harding plant cross-plume concentrations in 111-m LES domain at 1300 UTC (0700 LST); b) same, but for 1800 UTC (1200 LST); c) same, but for 0000 UTC (1800 LST).

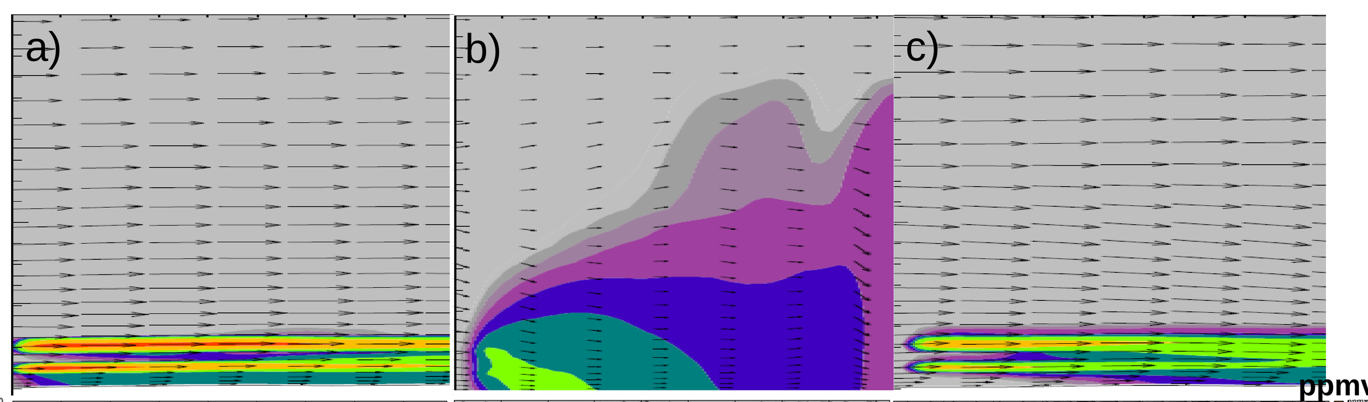
Figure 7 (below): a) Average Harding plant cross-plume concentrations for dual elevated release case in 333-m mesoscale domain at 1300 UTC (0700 LST); b) same, but for 1800 UTC (1200 LST); c) same, but for 0000 UTC (1800 LST).

5. PLUME CROSS-SECTIONS

We performed cross-wise averages of the CO_2 plume concentration along the trajectory axis (averaging distance of 1.67 km) in order to assess potential biases in plume concentrations by different physics configurations, and how the biases vary by horizontal and vertical distance.

As expected from the meteorology, the plume vertical extent is much greater during the daytime convective conditions than either near sunrise or sunset (Figure 5). During the daytime, the average concentrations are generally similar beyond about 7 km in the along-plume direction for both domains, though the LES has more variability in CO_2. Closer to the source, however, LES concentrations are considerably higher, and more confined to the ground (Figure 6).

We then performed the same analysis for a simulation where 65% of the Harding Plant release was at a height of 172 m, and 35% at 80 m, closely corresponding to the actual stack heights (Figures 7 and 8). Near dawn and dusk, both the mesoscale domain and the LES have dual plume structures with little vertical mixing – and are quite similar to each other. During the daytime, the impact of changing the release height has little effect beyond about 4 km. The LES is still characterized by higher average CO_2 concentrations and reduce vertical plume extent out to about 7 km.



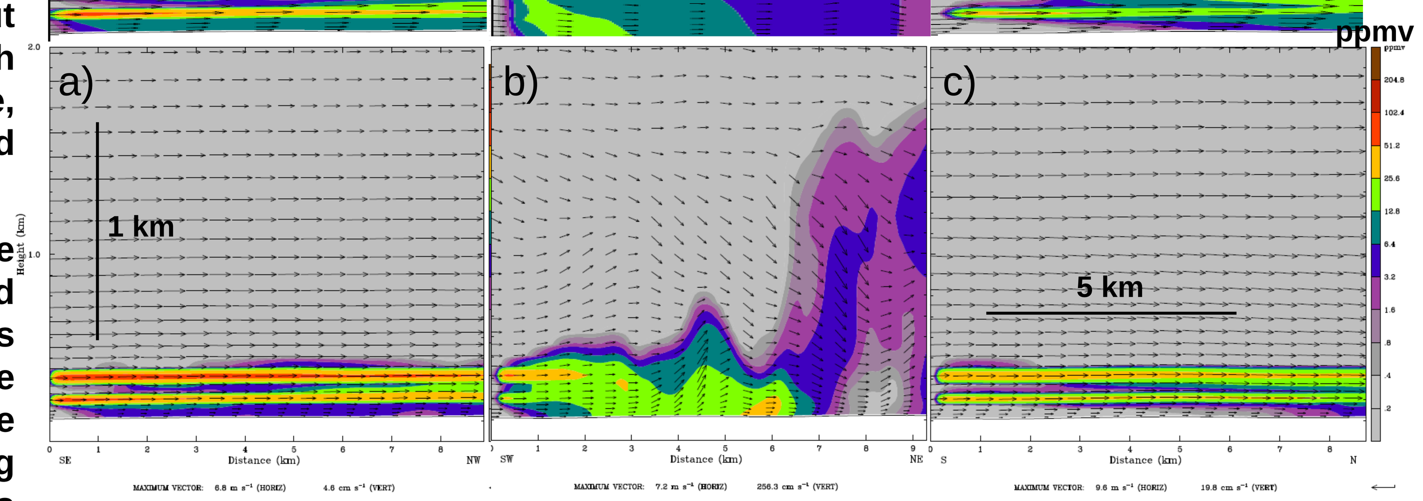


Figure 8 (above): a) Average Harding plant cross-plume concentrations for dual elevated release case in 333-m mesoscale domain at 1300 UTC (0700 LST); b) same, but for 1800 UTC (1200 LST); c) same, but for 0000 UTC (1800 LST).

6. CONCLUSIONS

For the dry ABL case simulated here, we found that daytime CO_2 average plume concentrations from the power plant did not depend much on either release height or turbulence physics (mesoscale or LES) beyond about 7 km from the source. The LES did reveal that considerable more spatial variability may exist in the concentration field than would be indicated by the mesoscale domain.

Closer to the source, the LES predicted larger average daytime concentrations and shallower plumes than did the mesoscale domain. The LES plumes also tended to be narrower in the horizontal – so while the LES might predict higher average concentrations, it might also predict higher probabilities of being outside the plume entirely.

7. FUTURE WORK

We intend to further quantify these findings in order to help obtain better estimates of the transport uncertainty associated with using a mesoscale model turbulence parameterization, as well as the minimum length scales for which mesoscale model-based transport is expected to be representative.

We also intend to compare the model concentration fields with tower observations from the INFLUX project to see if the LES results have empirical support, as well as expand the set of cases and range of meteorological conditions considered.

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